

OCEAN ACIDIFICATION FROM SPACE

Presented for...

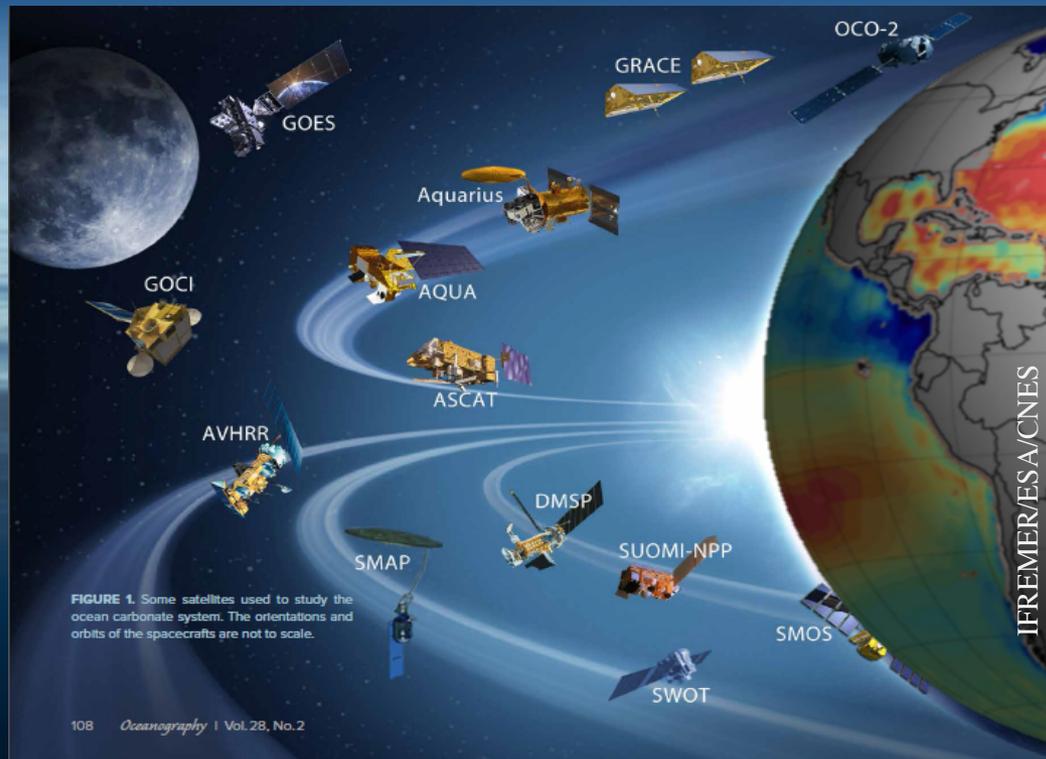
**NASA Carbon Monitoring System
Policy Speaker Series**

**NASA Goddard Space Flight Center
2 June 2016**

**National Oceanic & Atmospheric
Administration (NOAA)**

**Ocean Acidification Program
Office**

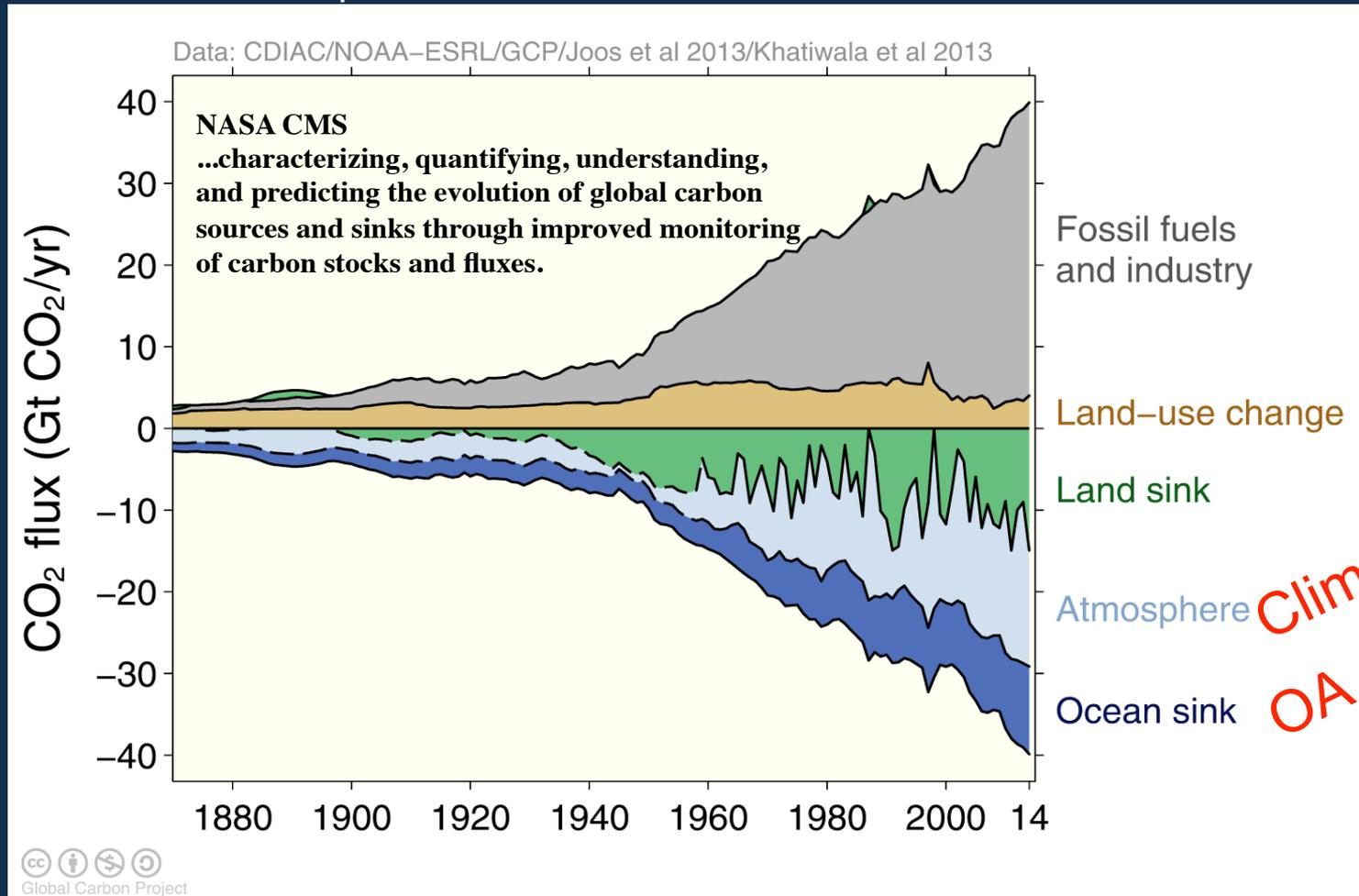
**Dwight Gledhill, NOAA OAP
Deputy Director**



<http://www.oceanacidification.noaa.gov/>

Global carbon budget

carbon sources from fossil fuels, industry, and land use change emissions are balanced by the atmosphere and carbon sinks on land and in the ocean



Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2015; Global Carbon Budget 2015

Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009

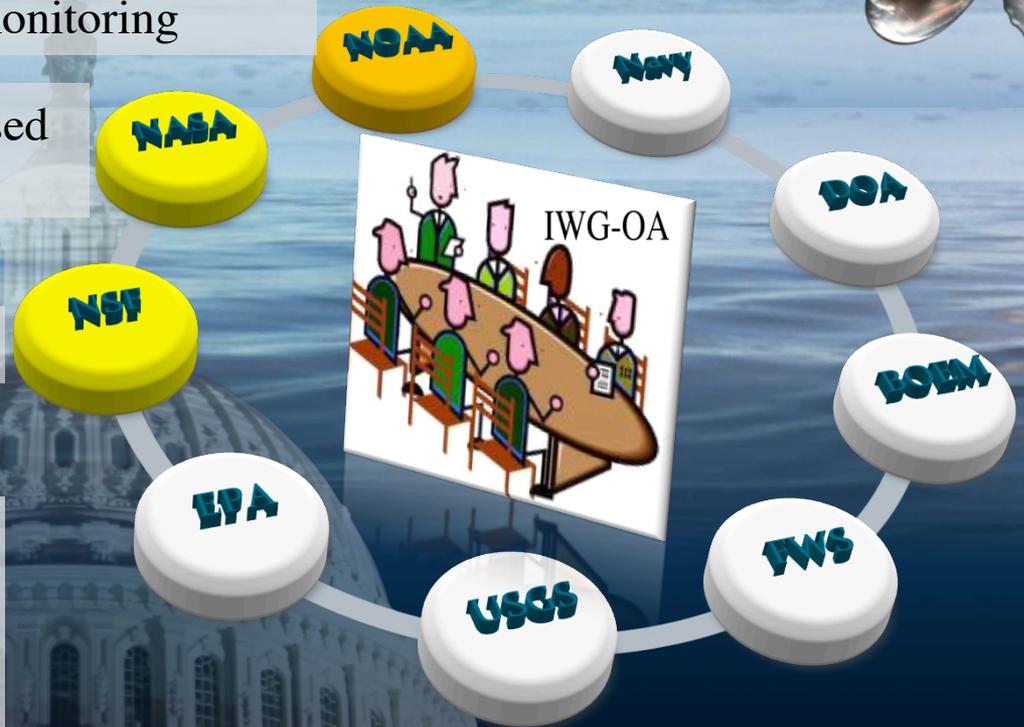
- NOAA: ...establish...[OAP] to conduct research, monitoring

- NASA: ...ensure space-based assets are applied

- NSF: ...competitive research

Defines ocean acidification as “the decrease in pH of the Earth’s oceans and changes in ocean chemistry caused by chemical inputs from the atmosphere, including carbon dioxide.”

Coordinate research, monitoring, and other activities consistent with the **Interagency Working Group on Ocean Acidification** strategic research plan.



Interagency Working Group on Ocean Acidification

U.S. Coordination on Ocean Acidification Science

Strategic Plan for Federal Research and Monitoring of Ocean Acidification

Vision

“A nation, globally engaged and guided by science, sustaining healthy marine and coastal ecosystems, communities, and economies through informed response to ocean acidification”

“...provide for an **assessment** of the impacts ...on marine ecosystems and the **development of adaption and mitigation strategies** to conserve marine organisms and marine ecosystems.”

March 2014



Coastal and estuarine acidification, to the extent that the cause of the acidification can be traced back to anthropogenic atmospheric inputs to the ocean, are assumed to be covered

U.S. Coordination on Ocean Acidification Science

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“A nation, globally engaged and guided by science, sustaining healthy marine and coastal ecosystems, communities, and economies through informed response to ocean acidification”

Prepared by the Interagency Working Group on Ocean Acidification

March 2014

Initial Report on Federally Funded Ocean Acidification Research and Monitoring Activities

Second Report on Federally Funded Ocean Acidification Research and Monitoring Activities

THIRD REPORT ON FEDERALLY FUNDED OCEAN ACIDIFICATION RESEARCH AND MONITORING ACTIVITIES

PRODUCT OF THE
Committee on Environment, Natural Resources, and Sustainability of the
National Science and Technology Council



April 2015



U.S. Coordination on Ocean Acidification Science

Strategic Plan for Federal Research and Monitoring of Ocean Acidification

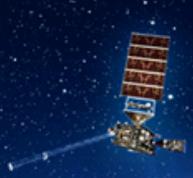
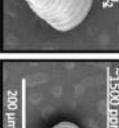
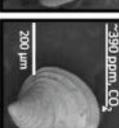
Highlighted Goals

- Monitoring trends and conditions
- Research marine life response
- Predictive modeling
- Ensure data quality
- Link experimental to field
- Vulnerability assessments
- Advance technology
- Devise adaptation strategies
- Foster OA literacy
- Implement engagement strategies
- Translate science for policy
- Ensure integrated and managed data

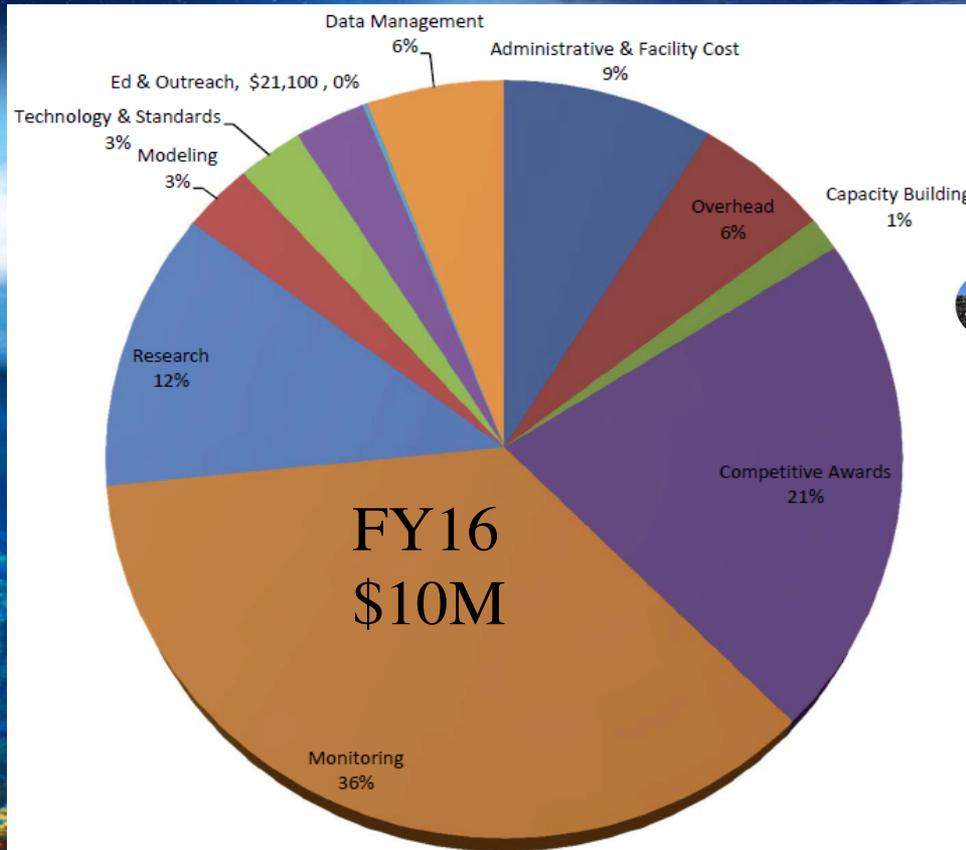
March 2014



NOAA's Ocean Acidification Program



SCIENCE. SERVICE. STEWARDSHIP.



Impacts to marine
 species.
 Others
 and resources
 and policy.

U.S. Coordination on Ocean Acidification Science

Strategic Plan for Federal Research and Monitoring of Ocean Acidification

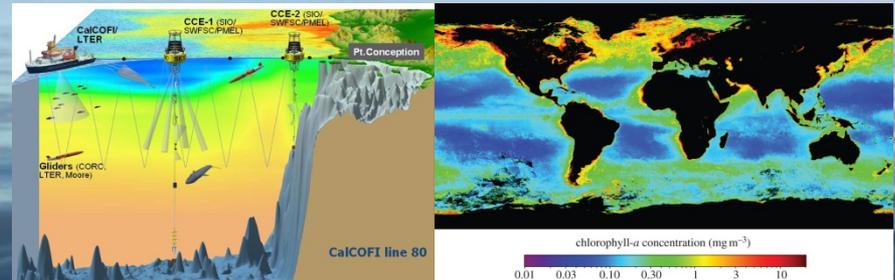
Vision

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Prepared by the Interagency Working Group on Ocean Acidification

March 2014

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts



Goals - The National Ocean Acidification Program monitoring plan should be designed to rapidly characterize the magnitude and extent of acidification ... at global, regional, and local scales..[to enable] projections of future impacts of ocean acidification...

Remote Sensing- ...provide synoptic observations of a range of physical and optical parameters that allow us to **model changes in the distribution of carbonate chemistry** within the surface ocean where no in situ observations are available.

Short-term (3-5 yrs)

- Explore use of OSSEs for in situ and **remote/satellite** and aircraft-based ocean acidification observation network design.

U.S. Coordination on Ocean Acidification Science

Strategic Plan for Federal Research and Monitoring of Ocean Acidification

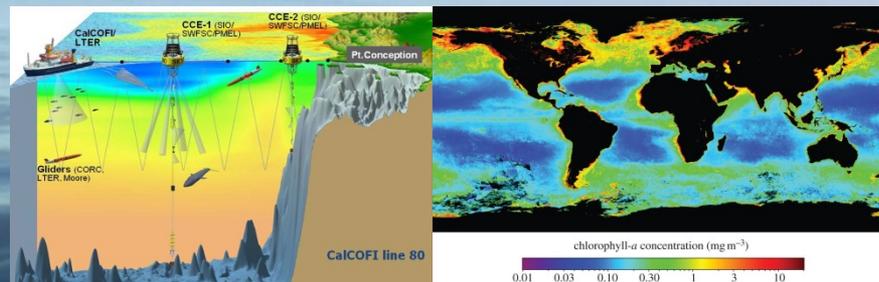
Vision

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Prepared by the Interagency Working Group on Ocean Acidification

March 2014

Theme 4. Technology Development and Standardization of Measurements

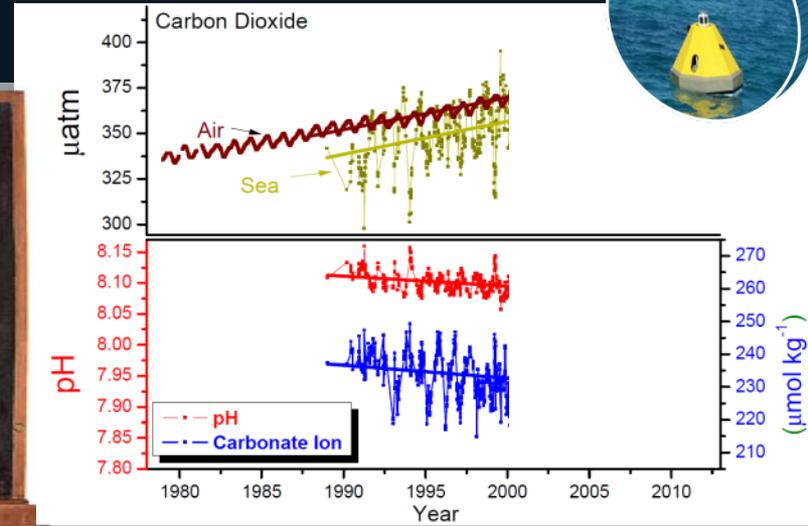
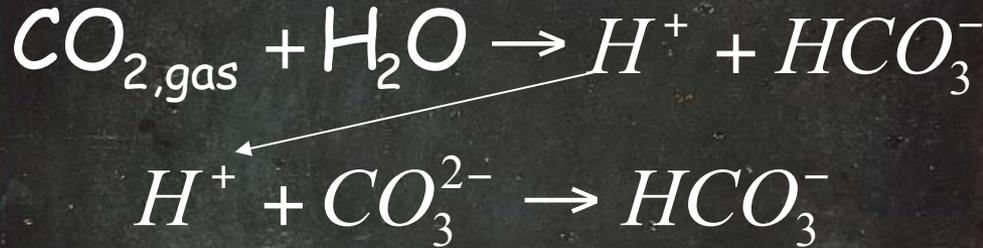


Goals - ... ensure that advancements in technology are developed systematically and quickly spread through the community.

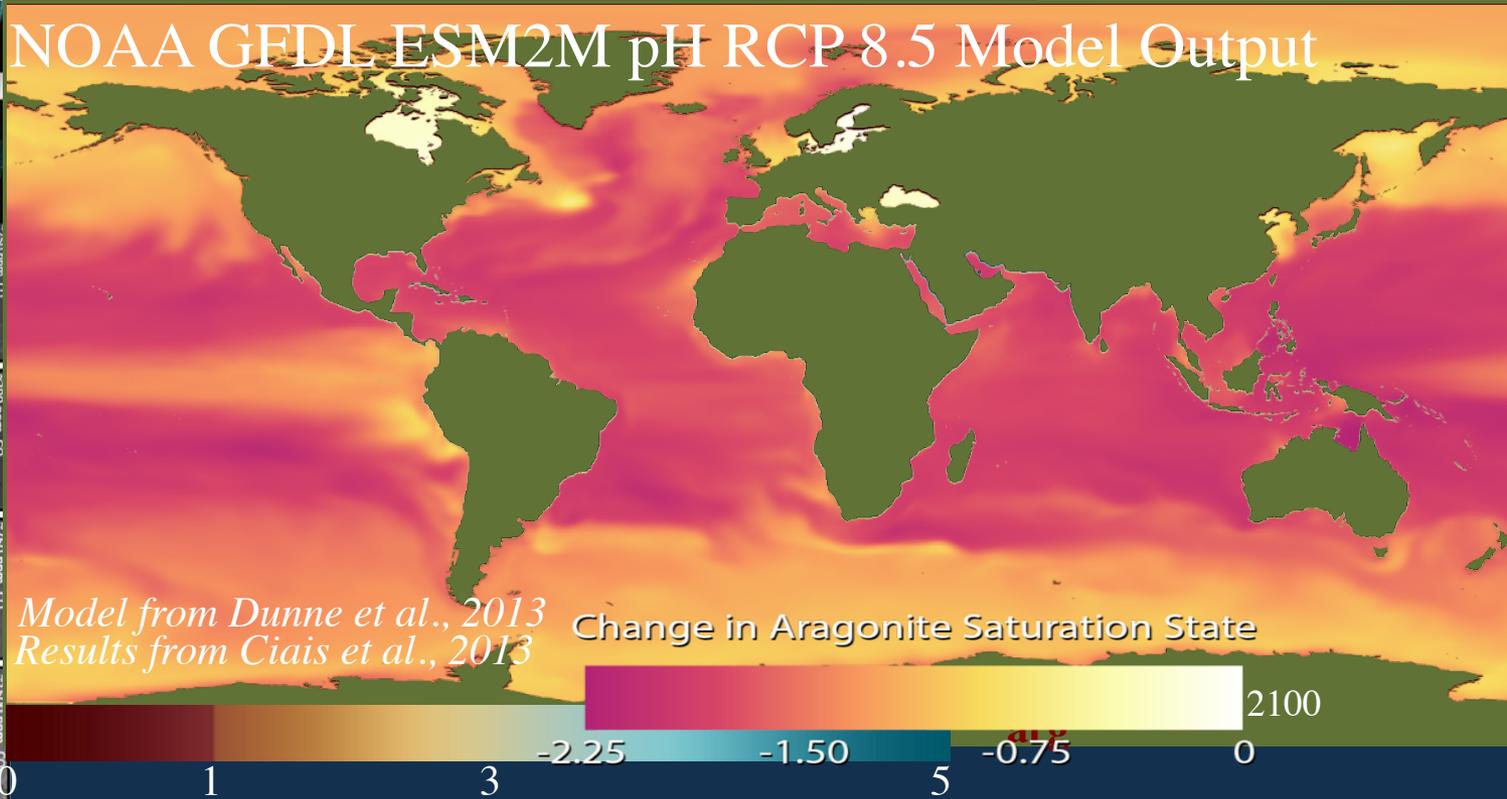
Long-term (10 yrs)

- Develop and commercialize instrumentation and techniques to improve capability to measure chemical (with special focus on DIC and TA) and biological variables over space and time, including affordable autonomous sensors, more accessible and affordable high-quality instrumentation, new remote sensing, and in situ technologies..

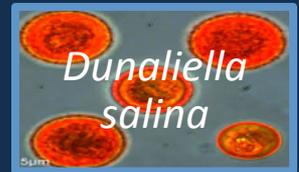
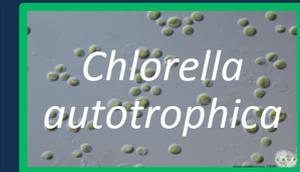
Ocean Acidification



NOAA GFDL ESM2M pH RCP 8.5 Model Output

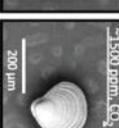
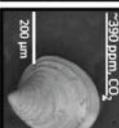


NOAA's OAP Species Response Research



Navigation controls: up arrow, down arrow, equals sign, ONGOING, question mark, 11, NOAA logo.

Controls on Surface OA Variability

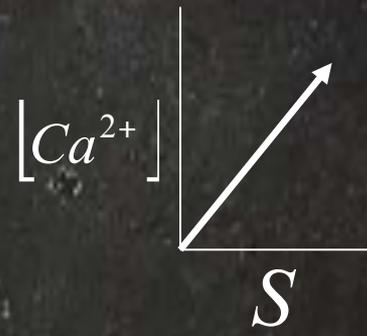


Saturation State

$$\Omega_{phase} = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{sp,phase}^*}$$

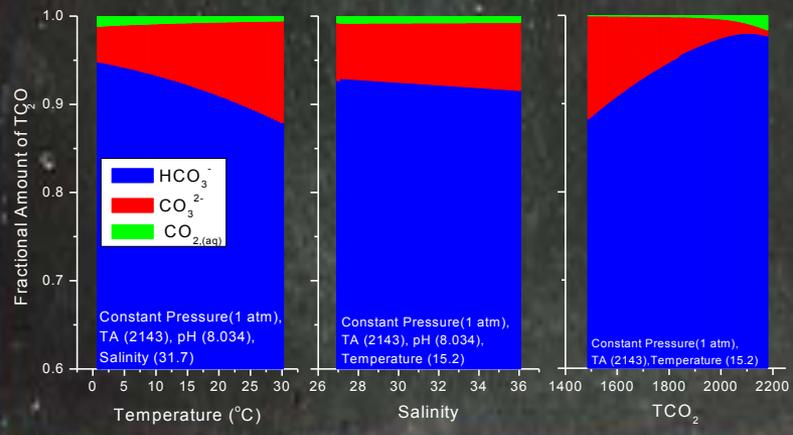
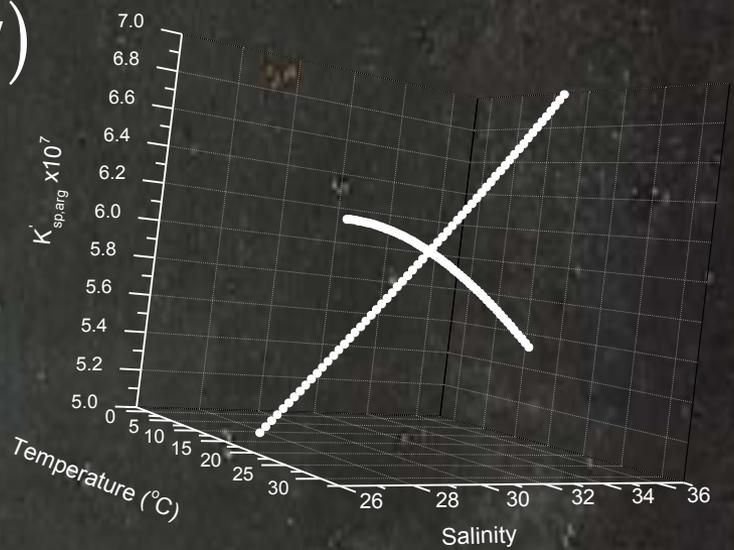
$\Omega > 1 = \text{precipitation}$
 $\Omega = 1 = \text{equilibrium}$
 $\Omega < 1 = \text{dissolution}$

$$[Ca^{2+}] = f(S)$$



$$K_{sp,phase}^* = f(S, T)$$

$$[CO_3^{2-}] = f(S, T, TCO_2)$$

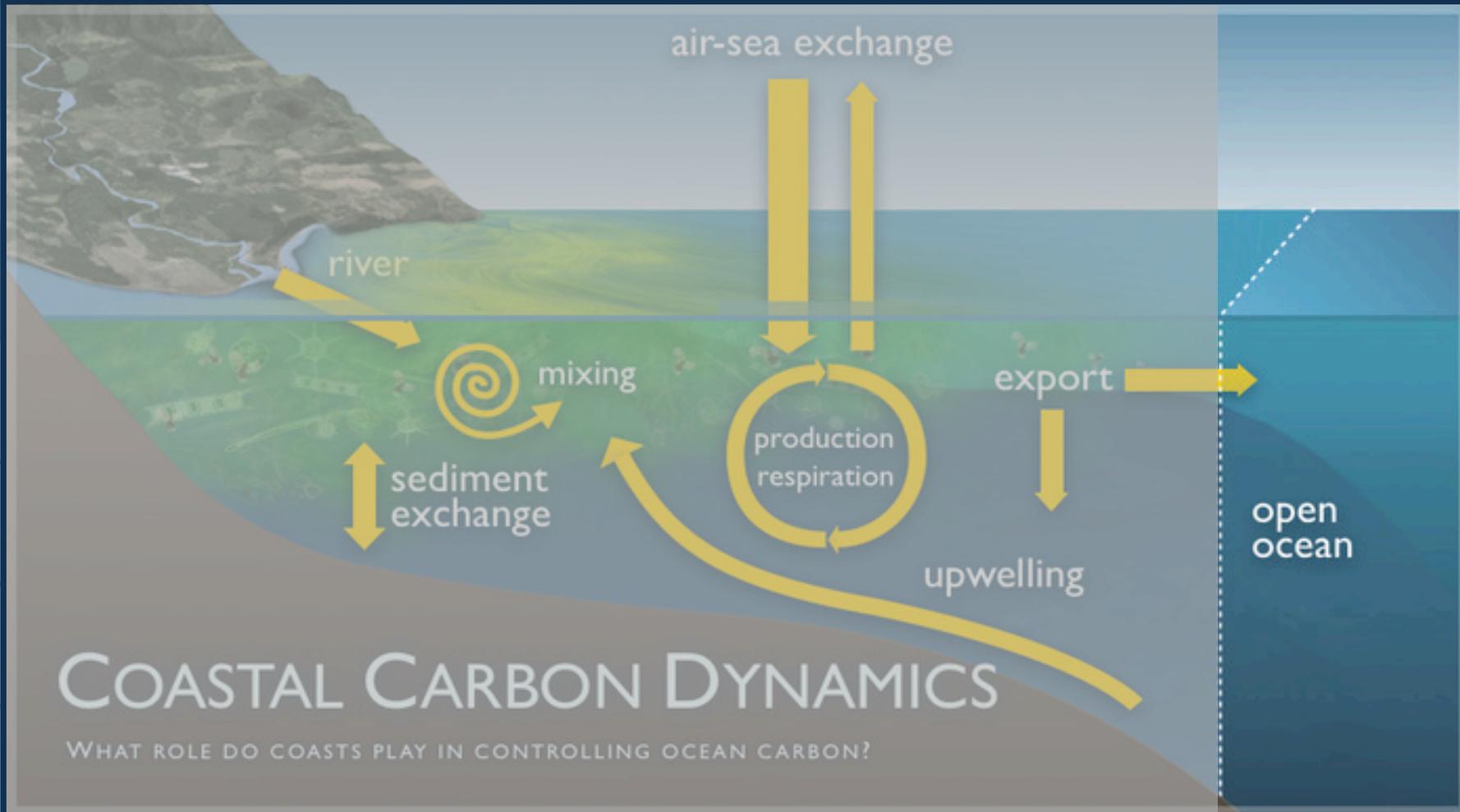


Ocean Acidification v1.0

$$\Omega = f(\text{temperature} \gg \text{mixing} \gg \text{biology} \gg \text{salinity} \gg \text{gas exchange})$$

v2.0

v1.0



Ocean Acidification v1.0

$$\Omega = f(\text{temperature} \gg \text{mixing} \gg \text{biology} \gg \text{salinity} \gg \text{gas exchange})$$

Application: temperature, solubility of carbon dioxide, mineral solubility

| Satellite | Agency Name | Sensor | Wavelengths | Geophysical Measurement | Effective Repeat Interval | Product Spatial Resolution (km) | Orbit | Launch Date |
|--|--|--|--------------------------|------------------------------|---------------------------|---------------------------------|---------------|-----------------------------|
| Several since 1978 | NOAA | Advanced Very High Resolution Radiometer (AVHRR) | Infrared (~12 μm) | IR radiance | Each ~daily | 1.1 | Polar | Several; 1978–present |
| Geostationary Operational Environmental Satellite (GOES) | NOAA | GOES Imagers | Infrared (~12 μm) | IR radiance | Each hourly | 0.75 | Geostationary | Several; 1975–present |
| Aqua and Terra | NASA | MODIS | Infrared (3.5 to 4.2 μm) | IR radiance | Each ~daily | 1 | Polar | 1999 (Terra) 2002 (Aqua) |
| Meteosat Second Generation | ESA | Spinning Enhanced Visible and InfraRed Imager (SEVIRI) | Infrared | IR radiance | 3-hourly | 11.16 (at nadir) | Geostationary | Several; 2008–present |
| Tropical Rainfall Measuring Mission's (TRMM) | NASA and JAXA | Microwave Imager (TMI) | Microwave (10.7 GHz) | Passive microwave emissivity | 3-day average | 25 | Polar | 1997 |
| Suomi-NPP | US National polar orbiting partnership | VIIRS | Infrared | IR radiance | ~daily | 0.75 | Polar | 2011 |

From: Salisbury et al., 2015. How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28(2):108-121, <http://dx.doi.org/10.5670/oceanog.2015.35>.



NOAA's OAP Funding Satellite-Based Projects

<http://www.coral.noaa.gov/accrete/oaps.html>

Ocean Acidification Product Suite for the Greater Caribbean Region, Gulf of Mexico, and US East Coast

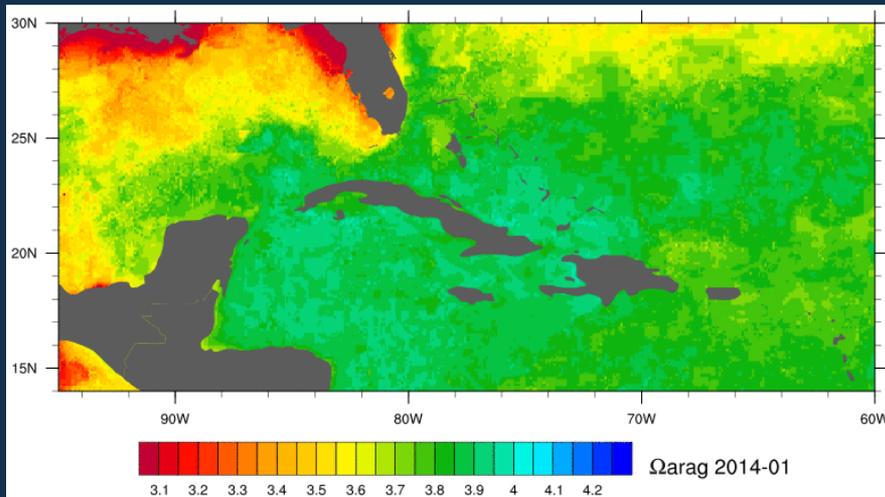
Van Hooideonik, Wanninkhof, Barbero (AOML)

$$A_T = a + b(\text{SSS} - 35) + c(\text{SSS} - 35)^2 + d(\text{SST} - 20) + e(\text{SST} - 20)^2$$

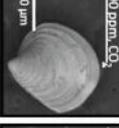
Lee, K., L. T. Tong, et al. (2006). "Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans." *Geophysical Research Letters* **33**.

$$pCO_{2,sw} = y_0 + A e^{(-K_0/B)} + pCO_{2,air}$$

Gledhill, D, R. Wanninkhof, et al. (2008). "Ocean Acidification of the Greater Caribbean 1996-2008." *JGR* **113**.



no single pCO₂ algorithm applicable at the global scale

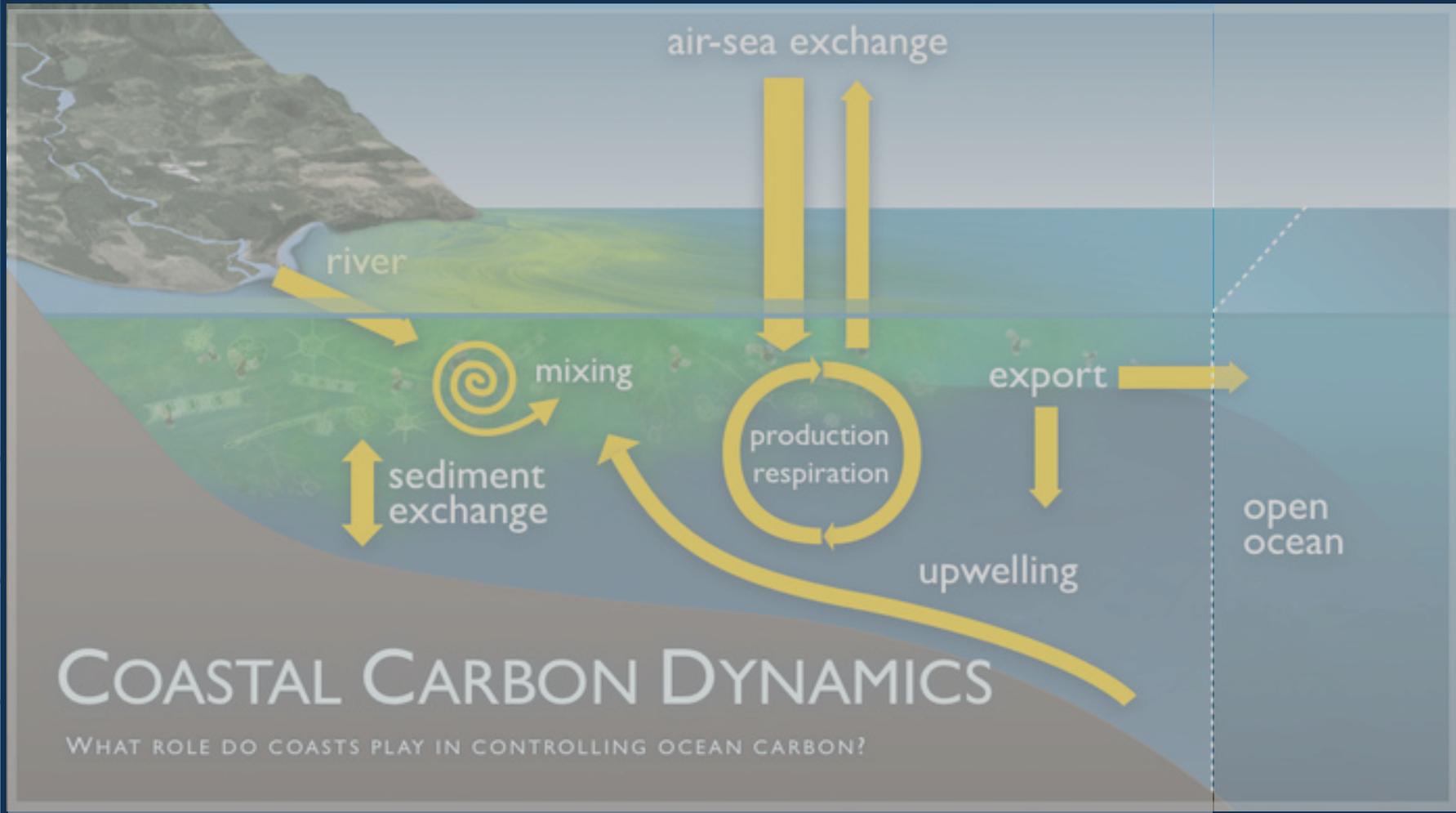
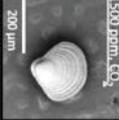
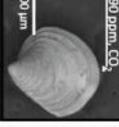
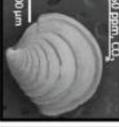


Ocean Acidification v2.0

$$\Omega = f(\text{temperature, salinity, temperature} \times \text{biology} \times \text{salinity} \times \text{gas exchange})$$

v2.0

v1.0



Ocean Acidification v2.0

$$\Omega = f(\text{biology} \gg \text{salinity} > \text{temperature} > \text{mixing} > \text{gas exchange})$$

Application: chlorophyll, particulate & dissolved colored carbon, particulate inorganic carbon, net primary & community productivity, ecological province designations

| Satellite | Agency Name | Sensor | Wavelengths | Geophysical Measurement | Effective Repeat Interval | Product Spatial Resolution (km) | Orbit | Launch Date |
|----------------|--|---|-------------------------|--------------------------------------|---------------------------|---------------------------------|---------------|-----------------------------|
| Aqua and Terra | NASA | Moderate Resolution Imaging Spectroradiometer (MODIS) | Visible – near infrared | Water leaving radiance (λ) | ~daily | 0.25, 0.50, and 1.00 | Polar | 1999 (Terra) 2002 (Aqua) |
| Suomi-NPP | US National polar orbiting partnership | Visible Infrared Radiometer Suite (VIIRS) | Visible – near infrared | Water leaving radiance (λ) | ~daily | 0.75 | Polar | 2011 |
| MERIS | European Space Agency | MEDium Resolution Imaging Spectrometer (MERIS) | Visible – near infrared | Water leaving radiance (λ) | ~daily | 0.3 | Polar | 2002 |
| COMS | Korea Ocean Satellite Center | Geostationary Ocean Colour Imager (GOCI) | Visible – near infrared | Water leaving radiance (λ) | 1 hour | 0.5 (at nadir) | Geostationary | 2009 |
| OceanSat 2 | Indian Space Research Organisation | Ocean Colour Monitor (OCM) | Visible – near infrared | Water leaving radiance (λ) | ~daily | 0.36 | Polar | 2009 |

PFT shifts: Satellite observations can be used to infer changes in the functional types that include calcifiers (coccolithophores), silicifiers (diatoms), and nitrogen fixers cyanobacteria)

Detection and quantification of coccolithophore PIC is invaluable providing spatiotemporal information about the conversion of TCO₂ to PIC

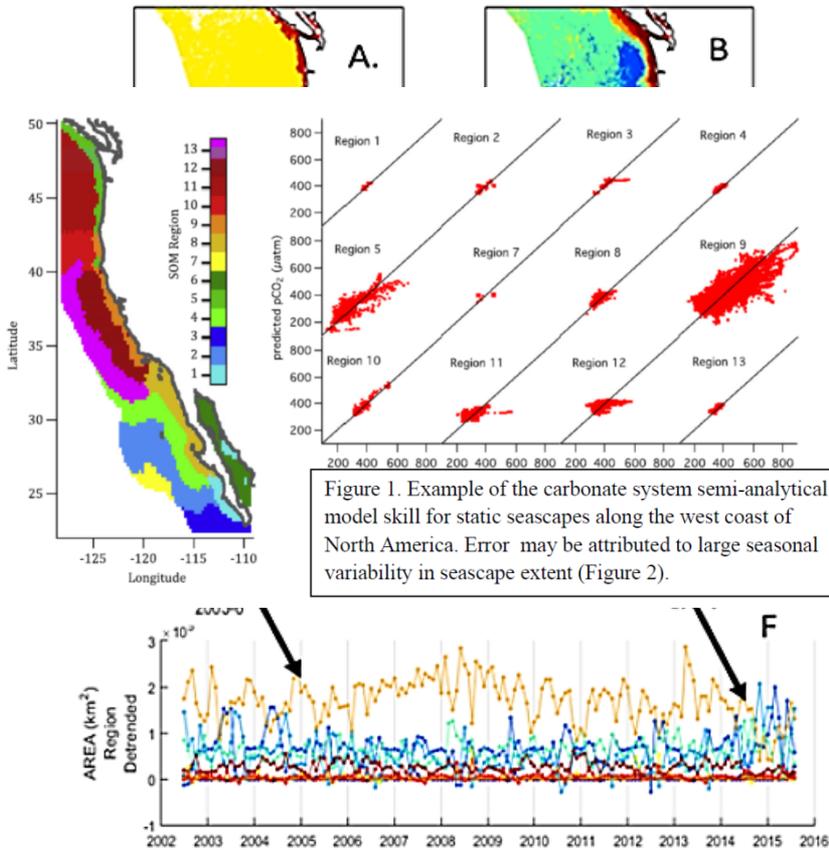
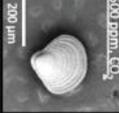
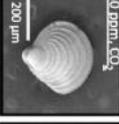
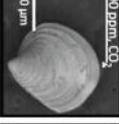
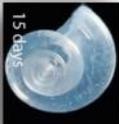
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NOAA's OAP Funding Satellite-Based Projects



Multi-Scale Prediction of California Current Carbonate System Dynamics

Hales (OSU), Kavanaugh & Doney (WHOI)



Objective: Embed semi-analytical OA prediction model within a dynamic classification of pelagic seascapes derived from satellite remotely sensed Variables (phytoplankton standing stock (chl-a), SST, and wind stress).

Application: Synoptic time series and nowcasts of surface OA conditions.

Salinity Sensors Application to OA

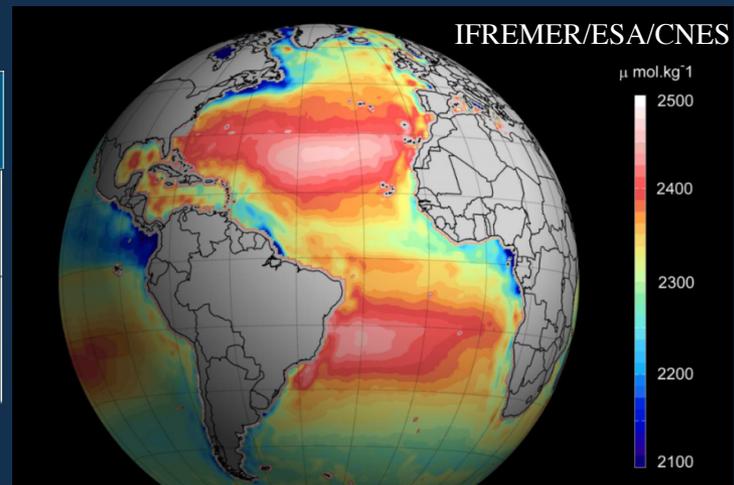
Application: salinity, total alkalinity, solubility of carbon dioxide, mineral solubility, mixing

| Satellite | Agency Name | Sensor | Wavelengths | Geophysical Measurement | Effective Repeat Interval | Product Spatial Resolution (km) | Orbit | Launch Date |
|---|---|--|----------------------------|-----------------------------|---------------------------|---------------------------------|-------|-------------|
| Soil Moisture Ocean Salinity (SMOS) | ESA | Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) | L-Band microwave (1.4 Ghz) | Passive microwave radiation | 10–30 day average | ~75 | Polar | 2009 |
| Satélite de Aplicaciones Científicas (SAC)-D, | NASA/ Comisión Nacional de Actividades Espaciales (CONAE) | Aquarius | L-Band microwave (1.3 Ghz) | Passive microwave radiation | 10–30 day average | ~100 | Polar | 2011 |

From: Salisbury et al., 2015. How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28(2):108-121, <http://dx.doi.org/10.5670/oceanog.2015.35>.

Close to the coast where pixel size limitations hamper salinity sensor capabilities, it is possible to retrieve salinity at higher resolution from established regional relationships between salinity and ocean color variables (Moller et al., 2010; Salisbury et al., 2011; Reul et al., 2013).

imprecision of ± 0.2 in satellite-derived salinity translates to $\pm 10-15 \mu\text{Mol kg}^{-1}$ in Talk.



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PUBLIC RELEASE: 16-FEB-2015

Satellite images reveal ocean acidification from space

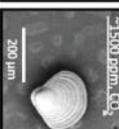
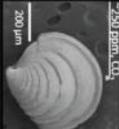
Pioneering techniques that use satellites to monitor ocean acidification are set to revolutionize the way that marine biologists and climate scientists study the ocean.

UNIVERSITY OF EXETER

From: Land et al., 2015. Salinity from Space Unlocks Satellite-Based Assessment of Ocean Acidification. *Environmental Sci. & Tech.* 49(4):1987-1994, DOI: 10.1021/es504849s.

Remote Sensing of Air-Sea CO₂ Exchange

Application: air-sea gas disequilibrium, secular changes in OA



| Satellite | Agency Name | Sensor | Wavelengths | Geophysical Measurement | Effective Repeat Interval | Product Spatial Resolution (km) | Orbit | Launch Date |
|------------------------|-----------------------|--|---------------------------------|-----------------------------|---------------------------|---------------------------------|-------|-------------|
| USAF F-16 through F-18 | US Air Force (DMSF) | Special Sensor Microwave Imager/Sounder (SSM/IS) | Various microwave 19 to 183 GHz | Passive microwave radiation | Sub daily | 17-74 | Polar | 2005 |
| MetOp-B | European Space Agency | Advanced SCATterometer (ASCAT) | 5.255 GHz (C-band) | Active radar | 29 days | 25-50 | Polar | 2012 |

| Satellite | Agency Name | Sensor | Wavelengths | Geophysical Measurement | Effective Repeat Interval | Product Spatial Resolution (km) | Orbit | Launch Date |
|---------------------------------------|-------------|----------------------|-------------|-------------------------|---------------------------|---------------------------------|-------|-------------|
| Orbiting Carbon Observatory-2 (OCO-2) | NASA | Triple spectrometers | NIR | Absorption (I) | 16 days | 1,000 | Polar | 2014 |

WHAT ROLE DO COASTS PLAY IN CONTROLLING OCEAN CARBON?

From: Salisbury et al., 2015. How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28(2):108-121, <http://dx.doi.org/10.5670/oceanog.2015.35>.



NOAA's OAP Funding Satellite-Based Projects

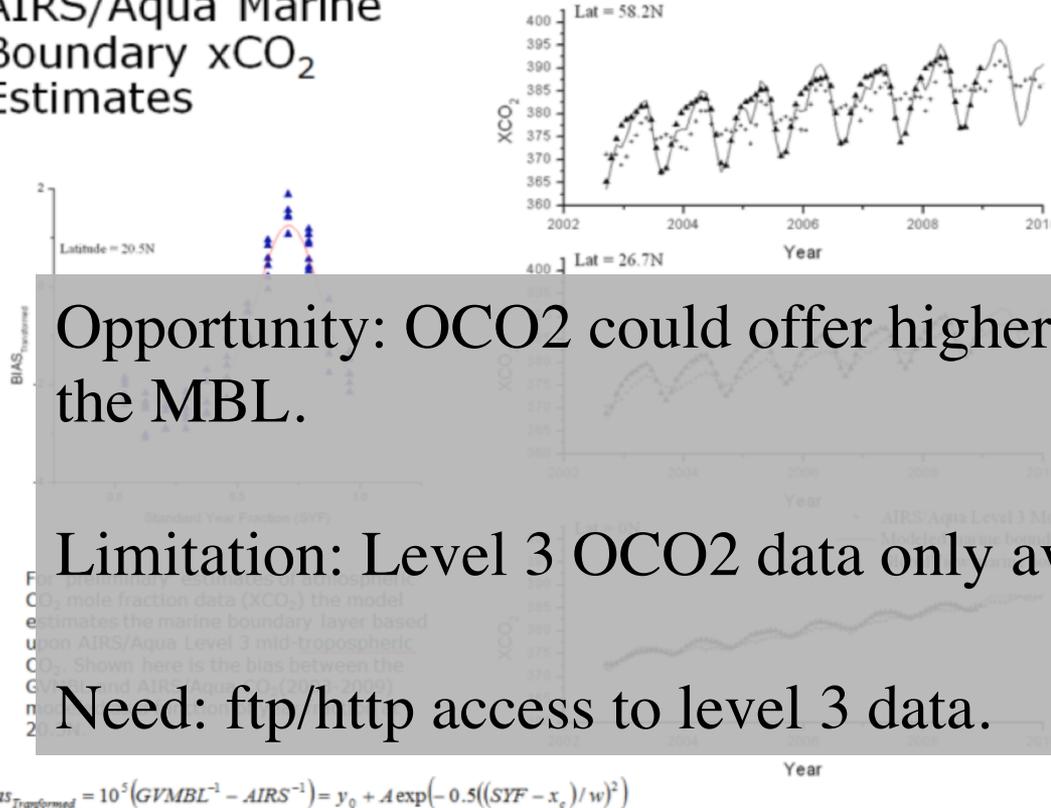
<http://www.coral.noaa.gov/accrete/oaps.html>

Ocean Acidification Product Suite for the Greater Caribbean Region, Gulf o Mexico, and US East Coast

Van Hooideonik, Wanninkjof, Barbero (AOML)



AIRS/Aqua Marine Boundary xCO₂ Estimates



Opportunity: OCO2 could offer higher resolution data at the MBL.

Limitation: Level 3 OCO2 data only available by request

Need: ftp/http access to level 3 data.

$$Bias_{Transformed} = 10^5 (GVMBL^{-1} - AIRS^{-1}) = y_0 + A \exp(-0.5((SYF - x_c)/w)^2)$$



NOAA's OAP Other Related Efforts

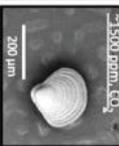
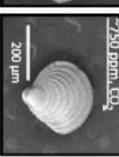
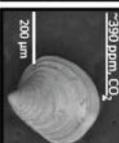
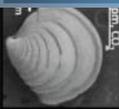
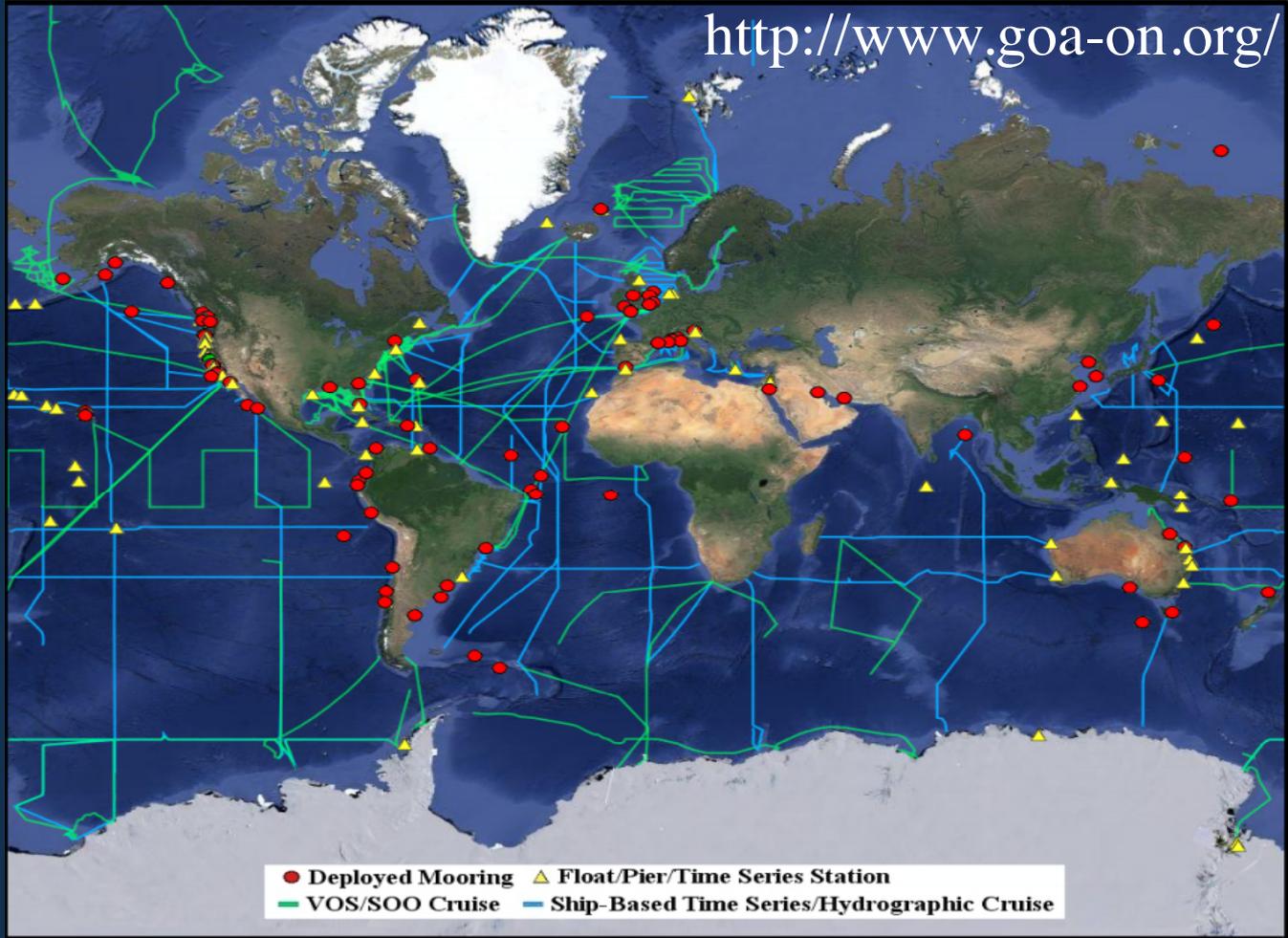
Global Ocean Acidification Monitoring

Step 0

HYDROGRAPHIC CRUISES
DOCUMENTING CARBON DISTRIBUTIONS IN THE OCEAN INTERIOR

VOLUNTEER OBSERVING SHIPS
DOCUMENTING CARBON DISTRIBUTIONS IN THE SURFACE OCEAN

BUOYS AND OTHER AUTONOMOUS SYSTEMS
DOCUMENTING TEMPORAL CHANGES IN OCEAN CARBON



>30 Nation's currently participating in GOA-ON

NOAA's Ocean Acidification Program

More information and data access



NOAA WEATHER OCEANS FISHERIES CHARTING SATELLITES CLIMATE RESEARCH COASTS

NOAA OCEAN ACIDIFICATION PROGRAM

Home About Us Areas of Focus Engagement Activities Opportunities What's New

Welcome to the NOAA Ocean Acidification Program! Ocean acidification is emerging as an urgent environmental and economic issue on our nation's east and west coasts and in many areas of the world.

CONNECT WITH NOAA OAP ON: [Facebook] [Twitter]

CONTACT US: noaa.oceanacidification@noaa.gov

NEWS: Scientists warn ocean food supply may be impacted by rising CO2. Carbon dioxide in the tropical Pacific Ocean is rising faster than expected. Ocean acidity is also rising rapidly. NOAA and partners release first federal ocean acidification strategic research plan. NOAA and partners release first federal ocean acidification strategic research plan. See Change Food for Marine's Role. Arctic Ocean Acidification Arctic Monitoring and Assessment Programme.

NOAA OCEAN ACIDIFICATION PROGRAM
Ocean acidification is occurring because the world's oceans are absorbing increasing amounts of atmospheric carbon dioxide, leading to lower pH and greater acidity. This is literally causing a sea change and threatening the fundamental chemical balance of ocean and coastal waters from pole to pole.

Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (CO₂ Working on Impacts of Ocean Acidification on Marine Biology and Ecosystems). Over the last 200 years, the atmospheric concentration of carbon dioxide has increased from 280 parts per million to over 380 parts per million due to the burning of fossil fuels (e.g., coal, gas, oil) and land use change (for instance, conversion of natural forest into crop production). Ocean acidification has potentially devastating ramifications for all ocean life, from the smallest, single celled algae to the largest whales.

As a requirement of the OCEANIC Act of 2009, the NOAA Ocean Acidification Program was officially established in May 2011. The NOAA OAP is an integral part of a much broader US research effort to increase our understanding about how (and how fast) the chemistry of the ocean is changing, how variable that change is by region, and what impacts these changes are having on marine life, people, and the local, regional, and national economies.

NOAA is coordinating closely with other federal agencies which have strong ocean acidification research or policy portfolios. These include the National Science Foundation (NSF), United States Geological Survey (USGS), National Aeronautics and Space Administration (NASA), Bureau of Energy Management (BEM), Department of State (DOS), U.S. Fish and Wildlife Service (USFWS), and the Environmental Protection Agency (EPA). See the Interagency Working Group for further information.

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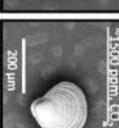
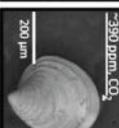
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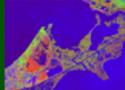
NOAA's Ocean Acidification Program

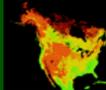
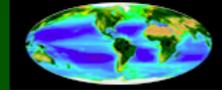



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| Solicitation: NNH16ZDA001N-CARBON | CARBON16 Proposals Due | Jun 15, 2016 |

3.6.3.1 Improved Observations

. . . studies which involve improved measurement of the carbonic acid system within poikilohaline environments may be considered, if proposed as a means to improving quantification of coastal carbon fluxes and achieving better constraint of coastal acidification processes.

<http://cce.nasa.gov/cce/opportunities.htm>

Concluding Thoughts

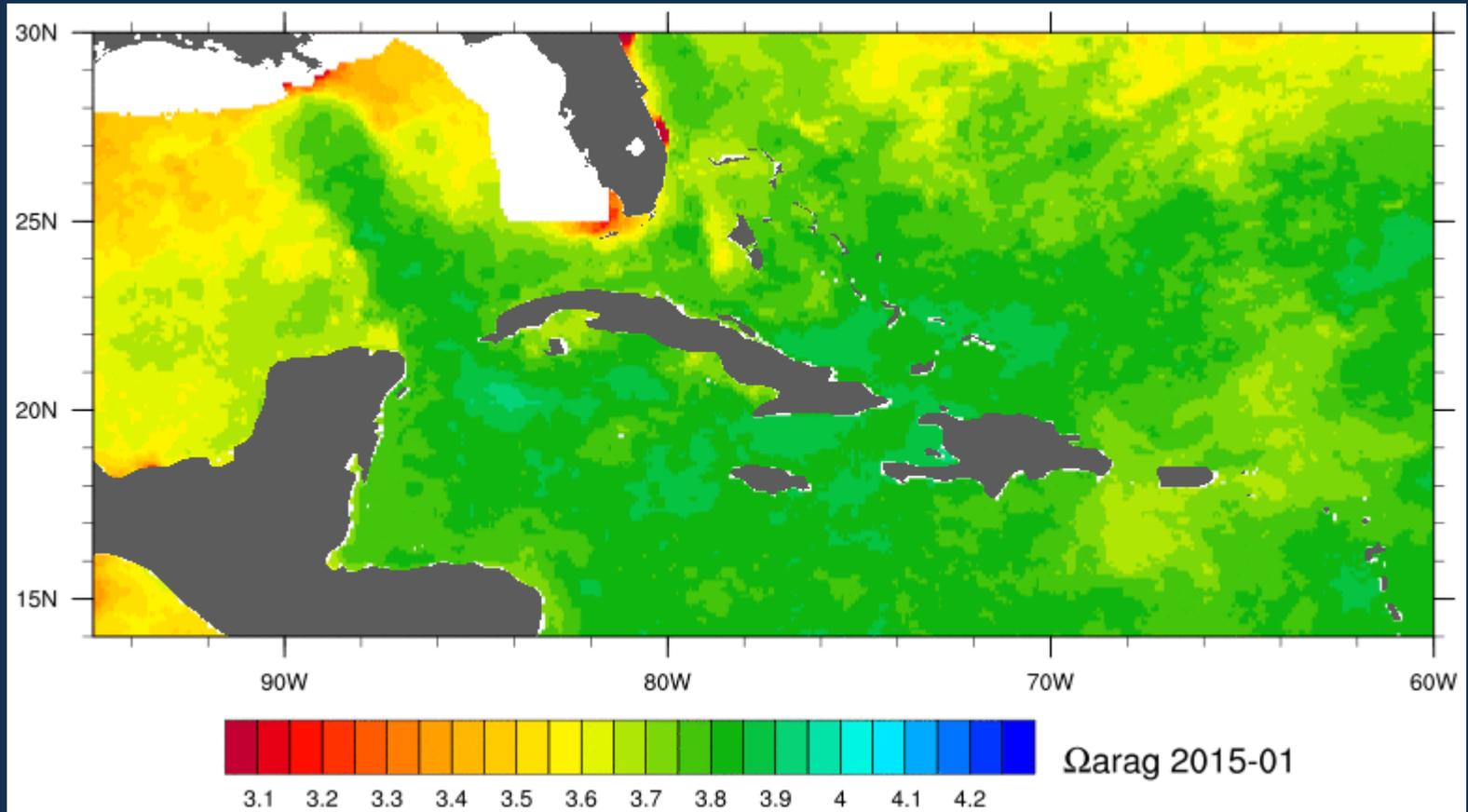
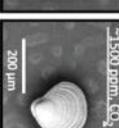
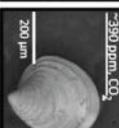
- The vulnerability of society to the impacts of ocean acidification differs regionally due to local chemistry, biology, and economic dependence. This heterogeneity creates an opportunity for information product needs.
- Most of the user needs for OA data products emerge from the marine resource management and industry community in the form of synthesis assessments. Not necessarily nRT.
- Satellite Ocean Color products are particularly of aid in improving synoptic mapping of OA with the coastal domain where biological forcing imparts a first-order effect to carbonate system dynamics.
- The primary utility of remote-sensing algorithms is presently in the ability to parameterize hydrographic linkages to natural variability and to bolster our understanding of baseline conditions.
- Limitations include resolution (i.e. SSS), land-masking, limited information on process rates. Algorithms have an expiration date requiring constant *in situ* verification and correction.
- Opportunities exist to further improve coastal/shelf algorithms by leveraging OAP supported geochemical surveys and other in-situ monitoring in support of the NOA-ON.

Discussion Points

- There isn't a direct remote-sensing proxy for essentially any of the carbonate parameters (maybe regional low-precision TA based on the current S products).
- The regression-based approaches that link directly to the individual parameters of interest (IPOIs) like pH, pCO₂, Ω are a-mechanistic, given IPOIs' non-linear dependence on TA, DIC.
- TA and DIC are the most mechanistically-linked to remotely-observable parameters, but those linkages require meta-modeling to approximate mixing and biological processes.
- Particle-based standing-stock observables have a rate and transport decoupling from the DIC and TA fields.
- The empirical relationships that allow the linkages between 3 and 4 are region-specific, which limits transferability of region-specific algorithms

- Burke Hales endorsed by Joe Salisbury

Thanks for listening



Let us not be too particular; it is better to have old secondhand diamonds than none at all.
 - Mark Twain